REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED
	Conference Proceeding	21-22 Aug 2003

4. TITLE AND SUBTITLE

Venturi Oxygen Stripping as a Ballast Water Treatment to Prevent Aquatic Invasions & Ship Corrosion

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

61153N

6. AUTHOR(S)

Marion Tamburri, Brenda J. Little, Gregory Ruiz and Peter McNulty

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/PP/7303/03/0051

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

20031217 282

14. ABSTRACT

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Our current investigations are providing the critical information required to evaluate the efficacy and feasibility of deoxygenation as a ballast water treatment to prevent aquatic invasions and tank corrosion.. These results will ultimately lead to a full-scale shipboard evaluation of deoxygenation as a cost-saving ballast water treatment.

15. SUBJECT TERMS

venturi oxygen stripping, ballast water treatment, aquatic invasions

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Brenda J. Little
Unclassified	Unclassified	Unclassified	SAR	15	19b. TELEPHONE NUMBER *(Include area code)* 228-688-5494

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Pubkey: 3576 NRLINST 5600.2

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4. AUTHOR

Title of Paper or Presentation Venturi Oxygen Stripping as a Ballast Water Treatment, ~~Evaluation of Deoxygenation as a Ballast Water Treatment to Prevent Aquatic Invasions and Ship Corrosion~~ to Prevent Aquatic Invasions + Ship Corrosion

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Office of Counsel,Code 1008.3		2/24/03	
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Dr. Mario N. Tamburri, Dr. Brenda J. Little, Dr. Gregory M. Ruiz, and Peter D. McNulty

Venturi Oxygen Stripping™ as a Ballast Water Treatment to Prevent Aquatic Invasions and Ship Corrosion

ABSTRACT

One of the most influential mechanisms for the introduction of aquatic nuisance species is transport in ship ballast waters. Although several ballast tank treatments to prevent transport of aquatic organisms appear promising, all existing approaches will result in significant costs to the shipping industry. The implementation of ballast water treatment measures would be hastened by providing the shipping industry with economic incentives for doing so. Our previous work suggests that deoxygenation may be such a treatment with benefit for ship owners by reducing corrosion, while simultaneously limiting the number of aquatic organisms surviving transport in ballast tanks.

Our current investigations are providing the critical information required to evaluate the efficacy and feasibility of deoxygenation as a ballast water treatment to prevent aquatic invasions and tank corrosion. Specifically, we are: (1) exploring a rapid, in-line oxygen stripping system developed by NEI Treatment Systems, Inc. to optimize the deoxygenation process, (2) examining the impact of this oxygen stripping technique on the immediate and long-term survival of natural Chesapeake Bay planktonic organisms, and (3) quantifying corrosion rates and establishing the mechanism under deoxygenated conditions (with particular emphasis on microbiologically influenced corrosion). These results will ultimately lead to a full-scale shipboard evaluation of deoxygenation as a cost-saving ballast water treatment.

STATEMENT OF PROBLEM

Invasions by non-native aquatic species are increasingly common worldwide in coastal habitats (Cohen and Carlton 1998). Estuaries in particular harbor large numbers of introduced species (Ruiz et al. 1997; 2000a). For instance, there are 234 known invasive species in the San Francisco Bay and Delta (Cohen and Carlton 1998), 119 in the Hudson River Basin (Mills et al. 1996), and 99 in Port Phillip Bay (Australian Southern coast; Hewitt et al. 1999). Even in these relatively well-studied areas, there are many more invaders to be discovered because surveys for non-native species have focused on conspicuous, macroscopic taxa.

Although the effects of many of these introduced aquatic species on habitats and communities remain largely unknown, some of them have had demonstrably strong negative influences. Harmful effects resulting from aquatic invasions include: decrease in abundance and even local extinction of native species (e.g., by the Japanese mudsnail *Batillaria attramentaria* in California; Byers 1999), alteration of habitat structure (e.g., by the Atlantic cordgrass *Spartina alterniflora* on the Pacific coast; Daehler and Strong 1996), and massive economic costs due to biofouling (e.g., by the European zebra mussel *Dreissena polymorpha* in the Great Lakes; Johnson and Carlton 1996).

Global shipping, which moves 80% of the world's commodities and is fundamental to international trade, inadvertently transports many aquatic organisms (see review by National Research Council 1996). In particular, ballast water (water that is pumped into dedicated ballast tanks or into empty cargo holds to increase draft, change trim, regulate stability, or maintain stress loads) is considered the most important vector responsible for transporting and introducing non-native aquatic species to new biogeographic regions (Carlton and Geller 1993). Vessels commonly pump in water in one port, and discharge it at another. Many planktonic organisms captured in ballast waters survive even lengthy journeys onboard ships. Examination of ballast water upon arrival of

vessels has revealed living and viable bacteria (McCarthy and Khambaty 1994; Ruiz et al. 2000b), protists (Galil and Huelsmann 1997; Pierce et al. 1997), dinoflagellates (Hallegraeff and Bolch 1991), diatoms, zooplankton, benthic invertebrates, and fish (Williams et al. 1988; Carlton and Geller 1993; Wonham et al. 2000). Increasing international traffic by increasingly large vessels translates into ever more enormous amounts of water, and planktonic organisms, being moved around the world by ballast water transport (e.g., the largest oil tankers can now have up to 40,000,000 gallons of ballast water capacity). Although other vectors, such as ship-fouling and aquaculture, are still important mechanisms introducing aquatic species to new places, none match ballast water transport for the sheer magnitude of organisms moved around the world (National Research Council 1996).

Theoretical and empirical studies have shown that "propagule pressure" (the number of larvae, spores, seeds, or dispersive adults introduced) is one of the best predictors of invasion success (Williamson 1996). Therefore, areas adjacent to large international ports are particularly susceptible to invasions. For example, the Chesapeake Bay has been inoculated with non-native species for approximately four centuries. Today, the Chesapeake receives annually greater than three billion gallons of ballast water from foreign ports around the world (Smith et al. 1999). This quantity of foreign ballast water greatly exceeds that released at other Atlantic ports of North America and has been implicated in many of the over 150 documented non-native species now found in the Chesapeake Bay (Ruiz et al. unpublished data).

Since transport in ballast tanks is a key source of introduced propagules, attention has focused recently on means of limiting ballast water introductions (National Research Council 1996). It has proven challenging to find an environmentally friendly technique that is effective at reducing introductions and yet also acceptable to the shipping industry in terms of safety, time, and cost. For instance, the offshore exchange of ballast water is currently recommended to reduce introductions (since coastal organisms are unlikely to invade open ocean areas, and vice versa), but the process is time-consuming, costly, cannot be performed in rough sea conditions, and has limited effectiveness in some environments and for certain vessel designs (e.g., Cooper et al. 2002; Ruiz et al. unpublished data).

Analysis of different ballast water treatments by the National Research Council (1996) suggested that intensive filtration, thermal treatment, and biocides were the most promising options. However, discharging warm water or water laden with biocides potentially threatens biological communities around ports, biocides can be dangerous to crew members, and fine filtration systems are expensive to install and maintain (National Research Council 1996). Recently, additional treatment options have been proposed such as ultraviolet radiation, centrifugation, and ozonation. However, unless mandated to do so by law, the shipping industry is unlikely to voluntarily implement any costly, time-consuming, or potentially dangerous procedures.

The implementation of ballast water treatment measures would be hastened by providing the shipping industry with economic incentives for doing so. Our previous work suggests that deoxygenation may be such a treatment with benefit for ship owners through corrosion prevention, while simultaneously limiting the number of aquatic organisms surviving transport in ballast tanks.

Corrosion of ballast tanks from exposure to seawater is commonly destructive and costly for individual vessels and the shipping industry as a whole. Currently painting and sacrificial anodes are used almost exclusively as the means to prevent ballast tank corrosion, but it is expensive and time-consuming. Investigators from Sumitomo Heavy Industries, Ltd. of Japan have therefore proposed an alternative corrosion prevention technique that purges oxygen from ballast tanks with nitrogen gas (Matsuda et al. 1999). This new anticorrosion technology was derived from the basic concept that removing oxygen from the ballast tanks will limit the oxidation of metallic structures and thus greatly reduce the problems associated with corrosion. Our initial proof-of-principle and laboratory studies on the effectiveness of deoxygenation to

prevent the transport on non-native species and the full-scale, field study on ballast tank corrosion demonstrated that this approach may both save the shipping industry money on corrosion prevention while removing a large proportion of the organisms typically found in ballast waters (Tamburri et al. 2002; summarized below).

The primary objective of our current work is to test the efficacy of deoxygenation in removing ballast water organisms while reducing ballast tank corrosion, using a series of experiments in the laboratory and in dock-side mesocosms (i.e., 25 gallon cylindrical tanks). Although the effects of low oxygen or hypoxia (< 1.0 mg/l oxygen) on aquatic organisms (see reviews by Grieshaber et al. 1994, Diaz and Rosenberg 1995; Tamburri et al. 2002) and corrosion (e.g., Hardy and Bown 1984; Lee et al. 1993a) are well documented, our current work is the first large-scale, direct investigation of both simultaneously. Furthermore, by conducting the experiments across different scales, we are collecting the critical data required to evaluate the feasibility of deoxygenation as a ballast water treatment.

BACKGROUND AND PREVIOUS WORK

Deoxygenation to Stop Invasions – The objectives of our previous work were to evaluate if deoxygenation used to reduce ballast tank corrosion could also successfully curb the introduction of aquatic organisms. Our publication in *Biological Conservation* (Tamburri et al. 2002) presents a synthesis and reanalysis of the relevant parts of the Japanese technical report describing an 18-month shipboard field study implementing this anticorrosion approach (Matsuda et al. 1999). In summary, Sumitomo Heavy Industries found that deoxygenating ballast waters (purging with nitrogen gas to drop oxygen levels to approximately 0.2 mg/l) decreases the rate of uniform corrosion to 10% of untreated ballast tanks and represents a significant saving for ship owners when compared to other corrosion prevention approaches currently available (approximately $80,000/year/vessel saved when compared to the standard painting and maintenance). These results are supported by the anecdotal observations of the Hellespont Group, who state that corrosion in ballast tanks on their tankers has been "completely arrested" after the addition of anodes and low-sulphur inert gasses.

To test whether deoxygenation may also limit invasion, we carried out laboratory oxygen tolerance experiments on the larvae of three widely introduced aquatic nuisance species (Australian tubeworm *Ficopomatus enigmaticus*, European zebra mussel *Dreissena polymorpha*, and European green crab *Carcinus meanas*) using oxygen levels comparable to those in the shipboard corrosion study (< 0.8 mg/l). Significant levels of mortality were found in nitrogen treated water after only two or three days (Figure 1).

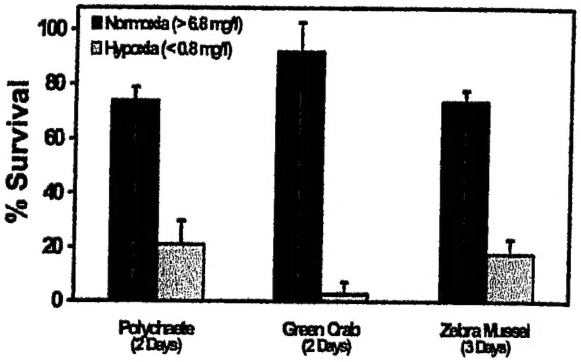

Figure 1. Mean percent survival (± SD) of *Ficopomatus enigmaticus* (polychaete), *Carcinus meanas* (green crab), and *Dreissena polymorpha* (zebra mussel) larvae after 2 or 3 days of being held in water open to air (normoxia) and in water where oxygen was removed by purging with nitrogen gas (hypoxia). From Tamburri et al. 2002.

Two separate literature reviews of oxygen tolerance for various aquatic species further support the conclusion that few organisms will be able to withstand extended periods (more than 48 hours) of exposure to deoxygenated ballast water (Table 1). For example, by far the most abundant animals overall found in ballast water are copepod crustaceans (Carlton and Geller 1993; Smith et al. 1999) and shallow water and estuarine species that are unable to withstand 24 hours of exposure to hypoxia (e.g.,

Roman et al.,1993; Lutz et al. 1994; Stalder and Marcus 1997).

Table 1. A representative sample of time until significant mortality (LD_{50}, LT_{50}, or survivorship in treatment significantly less than control) was found for aquatic organisms held under various low oxygen concentrations. From Tamburri et al. 2002.

Species	O_2 level	Time to sign. mort.	Source
Astronotus ocellatus fish - adults	0.4 mg/l	24 hours	Muusze et al. 1998
Ophiura albida brittle star - adults	0.1 mg/l	60 hours	Vistisen and Vismann, 1997
Gammarus pseudolimnaeus amphiod - adults	1.5 mg/l	24 hours	Hoback and Barnhart, 1996
Platichthys flesus fish - juveniles	1.0 mg/l	2 hours	Tallqvist et al. 1999
Loimia medusa polychaete - adults	0.5 mg/l	72 hours	Llanso and Diaz, 1994
Meganyctiphanes norvegica krill - adults	1.8 mg/l	2 hours	van den Thillart et al. 1999
Cancer irroratus crab - larvae	1.7 mg/l	4 hours	Vargo and Sastry, 1977
Crassostrea virginica oyster - larvae	0.02 mg/l	18 hours	Widdows et al. 1989

Small plant and algal parts (fragments, spores, and seeds) as well as single-celled phytoplankton, protoctists, fungi, and bacteria are also often transported in ballast water. These microscopic components of ballast water have not been thoroughly characterized. However, it appears from our reviews that their tolerances for low oxygen environments will vary greatly. There are examples of species that are very sensitive to hypoxic conditions (e.g., filamentous fungi, Padgett et al. 1989; zoospores of the seaweed *Undaria pinnatifida*, Mountfort et al. 1999), as well as counter-examples of species that can withstand low oxygen levels (e.g., resistant cysts of dinoflagellates, Hallegraeff 1998). Marine bacteria, in particular, will have dramatically different responses to the conditions created in nitrogen treated ballast tanks. While most obligate aerobic strains will be unable to grow over extended periods of hypoxia, some facultative and obligate anaerobic bacteria may actually thrive under the conditions found in treated ballast. We therefore conclude that ballast water deoxygenation (maintaining hypoxia) would likely be highly effective at reducing introductions of aquatic animals (larvae, juveniles, and adults stages) but may have mixed success at eliminating introductions by members of other taxa.

Although other ballast water treatment options might be more comprehensively effective, they come at greater environmental and financial cost. For example, biocides may be hazardous for the crew as well as for native organisms in the vicinity of the ballast discharge (National Research Council 1996). Moreover, these techniques come at a significant price for ship owners. Clearly, until required to do so, the shipping industry is unlikely to voluntarily install expensive ballast water treatment technologies. Indeed, Mountfort et al. (1999), who did not consider the anticorrosion benefits, concluded that deoxygenation of ballast water with nitrogen was reasonably effective at killing aquatic organisms but impractical for shipboard operations due to financial costs. In contrast, we propose that widespread voluntary adoption of deoxygenation may result if the economic benefits for controlling corrosion are demonstrated definitively and become well known. While ballast water treatments have been controversial, raising conflicts between environmentalists and ship owners, we feel deoxygenation represents a working solution that should appeal to both parties.

Ballast Tanks Corrosion – The vast majority of the world's fleet of ships, including military and

commercial vessels, are constructed of carbon steel. Steel corrodes quickly when exposed to oxygen and water. Ocean-going vessels are particularly susceptible to corrosion, due to the accelerated corrosion rate in exposure to salt water. Corroded steel structures on a vessel decrease seaworthiness so extensive measures are taken to prevent corrosion and, inevitably, in repair. The cost to prevent, maintain, and repair corrosion on individual vessels can run into the millions of dollars (e.g., $5.5 million to replace 1400 tonnes of ballast tank steel on *Wind Conquest*, Marine Engineering Review 1991).

One area in a ship where corrosion is of particular concern is in the ballast tanks. Prolonged exposure of the ballast tank structure to water (often salt water) creates a condition conducive to rapid corrosion. The cost to paint ballast tanks is typically $5.00 to $10.00 per square meter with the cost to repair corroded areas at approximately $500 per square meter (Fairplay 1993). With large cargo vessels and oil tankers having hundreds of thousands of square feet of ballast tank surface area, preventing and treating corrosion is extremely costly.

Therefore, any measure for controlling aquatic invasive species in ballast tanks cannot be evaluated without consideration of the impact on corrosion. For example, both chlorination (McCraken 2001) and ozonation (Andersen 2001) of seawater are known to exacerbate corrosion of steel. Clearly, removal or reduction of oxygen will eliminate or reduce direct oxidation reactions related to corrosion. However, deoxygenation could increase corrosion resulting from the activities of naturally occurring microaerophilic, facultative or obligate anaerobic bacteria. Acid-producing bacteria (APB) and sulfate-reducing bacteria (SRB) grow under anoxic conditions and produce corrosive metabolic by-products (organic acids and sulfides, respectively).

The corrosion rate of carbon steel is not influenced by pH over the range of 4.5 to 9.5 in distilled and tap waters (Boyer and Gall 1985). Over this range, corrosion products maintain a pH of 9.5 at the metal surface. Below pH 4.0, hydrogen evolution begins and corrosion increases dramatically. Although it is extremely unlikely that APB will change the bulk pH of carbonate buffered seawater, APB can reduce pH locally under colonies and produce corrosion in carbon steel (Pope 1995).

All seawater contains 2 gm l^{-1} sulfate than can be reduced to sulfide by SRB in the absence of oxygen. Reviews by Miller and Tiller (1970), Iverson (1974) and Postgate (1979) provide examples and details of microbiologically influenced corrosion of iron and mild steel under anaerobic conditions caused by SRB. Microbiologically influenced corrosion failures have been reported for mild steel piping and equipment exposed in the marine environment (Sanders and Hamilton, 1986; Eidsa and Risberg 1986; Eashwar et al. 1990) soil (King et al. 1983; Kasahara and Kajiyama 1986; Alanis et al. 1986; Pope et al. 1988; Dias and Bromel 1990), oil refining industry (Winters and Badelek 1987), fossil fuel and nuclear power plants (Soraco et al. 1988; Licina 1988, Pope 1986 and 1987; Bibb 1986) and process industries (Pacheco, 1987; Honneysett 1985; Tatnall et al. 1981). Deoxygenation can also result in putrefaction, anaerobic breakdown of sulfur-rich proteins, and levels of sulfides will not be limited to the sulfate concentration in the seawater. Sulfide reacts with iron oxide, formed in the atmosphere or in oxygenated seawater, to produce a non-tenacious iron sulfide layer that can be removed with stress or converted back to an oxide by the introduction of oxygen. In either case the sulfide layer is not uniformly removed or oxidized, creating adjacent anodic and cathodic regions and aggressive corrosion.

The most corrosive operating condition is one in which carbon steel is exposed to alternating oxygenated/deoxygenated conditions (Hardy and Bown 1984; Lee et al. 1993a; Lee et al. 1993b). Under constant oxygenation an oxide will form that provides corrosion resistance. Under anaerobic conditions a sulfide layer will form and corrosion rate will decrease until oxygen is introduced. The result of alternating operating conditions is severe pitting. Additionally, concentrations of sulfides can produce sulfide assisted stress corrosion cracking in carbon steel. Most reported cases of SRB induced corrosion of carbon steel in marine

waters are in environments with some dissolved oxygen in the bulk medium (Hamilton 1986). Anaerobic conditions and sulfides form within marine biofilms at biofilm/metal interfaces, independent of bulk oxygen concentrations. Exposure of iron sulfide corrosion products to oxygen creates differential aeration cells and localized corrosion. However, because aerobic microorganisms form biofilms, continuous deoxygenation to prevent biofilm production has been suggested as a way to reduce microbial induced corrosion (Lutey 200; Pope and Pope 2001).

CURRENT INVESTIGATIONS

The basic objective of our ongoing research is to quantify the effectiveness of deoxygenation in removing ballast water organisms while reducing ballast tank corrosion. Specifically we are: (1) exploring a rapid, in-line oxygen stripping system developed by NEI Treatment Systems, Inc. to optimize the deoxygenation process, (2) examining the impact of this oxygen stripping technique on the immediate and long-term survival of natural Chesapeake Bay planktonic organisms, and (3) quantifying corrosion rates and establishing the mechanism under deoxygenated conditions (with particular emphasis on microbiologically influenced corrosion).

Optimizing Deoxygenation – A key to the success of deoxygenation as a ballast water treatment is to design the most efficient method for maintaining levels of oxygen in tanks that both kills the majority of aquatic organisms while also reducing corrosion rates – below 1.0 mg/l. Evaluations of several approaches and a series of pilot studies have led to the conclusion that Venturi Oxygen Stripping represents the most effective and economical method of deoxygenation for use aboard vessels (NEI Treatment Systems, Inc., unpublished data).

The deoxygenation method proposed by Sumitomo Heavy Industries for ballast water treatment entails bubbling an inert gas into the ballast tanks after they have been filled. The shipboard trial by Matsuda and colleagues (1999) included vertical pipes installed into a ballast tank from which pure nitrogen gas was pumped into the water for the "sparging" of oxygen. The tank was also sealed at the deck to permit nitrogen purging of the headspace. This method may achieve some deoxygenation through the contact of the nitrogen bubbles with the water, but primarily relies on diffusion of oxygen through the water surface in the tanks. Although hypoxic conditions were achieved, the sparging and purging of oxygen took days and relied on both the presence of a large headspace in the ballast tank filled with nitrogen gas (a free surface condition that is typically avoided since it can destabilize the vessel as water moves within tanks) and on large volumes of expensive inert gas. Although the basic principles are sound and experimental results significant, the method used by Sumitomo Heavy Industries for deoxygenation appears to be inefficient and relatively costly to employ (approximately $3.5 million for installation on a vessel).

Other deoxygenation methods (e.g., vacuums, horizontally placed diffuser plates) use techniques with varying degrees of effectiveness. However, our investigations suggest that the most efficient way to remove oxygen from ballast water is through introducing microfine bubbles of an inert gas as water is being pumped into the tanks. The smaller a bubble, the higher the ratio of surface area to volume and thus the higher gas-to-water contact surface where transfer takes place. Therefore, we have begun work with NEI Treatment Systems, Inc. to optimize the deoxygenation of ballast water through Venturi Oxygen Stripping. Initial laboratory results show that the time until low-oxygen equilibrium conditions in the water are reached can be less than four seconds, the oxygen stripping system will require very few modifications for shipboard applications, and most importantly, it may be much more cost effective than the treatment system proposed by Sumitomo Heavy Industries described above.

Survivorship of natural planktonic organisms subjected to deoxygenated water – Dockside, mesocosm experiments are being conducted at the Chesapeake Biological Laboratory (CBL), University of Maryland Center for Environmental Science, in Solomons, Maryland (Figure 2).

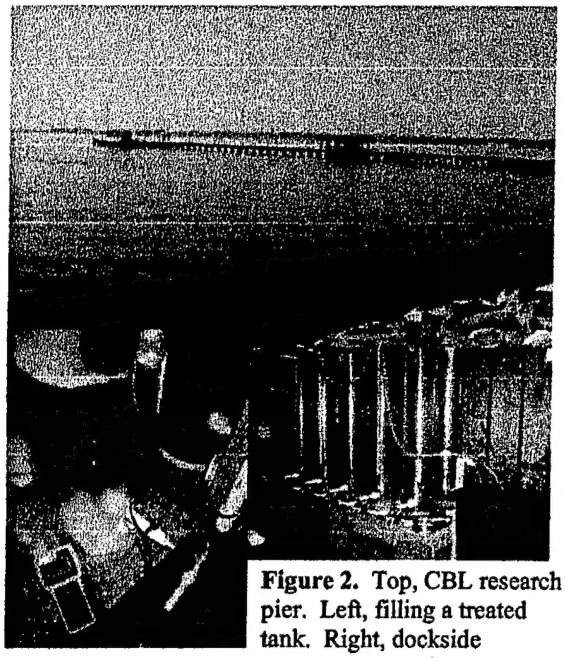

Figure 2. Top, CBL research pier. Left, filling a treated tank. Right, dockside mesocosm experimental setup.

Natural seawater is pumped from one meter below the surface into 10 identical 20-gallon, airtight acrylic cylinders, held inside a laboratory at the end of the CBL pier. All water first passes through a 1 cm screen – the mesh size commonly used to restrict intake into ship ballast tanks. In five control cylinders, seawater is delivered directly from the pump. However, in five treated cylinders, the seawater first passes through the rapid, in-line oxygen stripping system. Physical conditions are monitored throughout the experiments with oxygen, temperature, and conductivity sensors sealed within the cylinders. Oxygen levels in the control cylinders are always above 8.0 mg/l whereas water in the treated cylinders enters and remains hypoxic (< 0.8 mg/l) throughout the experiments.

To examine mortality over time as a result of deoxygenation, one treated and one control cylinder are drained completely through a bottom valve 1, 24, 48, 72, and 96 hours after filling. The treated and control cylinder at each sampling period are then compared for abundance and mortality of three separate planktonic community components.

- Zooplankton – the entire volume is sieved through a 50 μm screen and evaluated for total abundance and living versus dead individuals. The percentage of living individuals will be quantified by examining reactivity or movement under dissecting microscope.
- Phytoplankton – water passing through the 50 μm sieve are analyzed for chlorophyll a concentrations. Subsamples are examined under a compound microscope to identify major algae groups and cell abundance will be determined by flow cytometry.
- Bacteria – the density of bacterial cells are determined by flow cytometry and subsamples of the water are used to determine total plate counts of culturable bacteria.

Additionally, subsamples of abundant zooplankton (such as copepods) that are scored as dead after the 48-hour deoxygenation treatment are placed aerated natural seawater to determine their ability to recover and resume swimming after removal from hypoxic conditions.

This process is being repeated five times during the seasons when planktonic organisms are most abundant (April through September 2003) in the Chesapeake Bay.

Initial results suggest that in addition to hypoxia alone causing rapid mortality (greater than 99% of organisms 50 μm or larger killed in less than 48 hours), the physical/mechanical disturbances experienced as organisms pass through the Venturi injector will also kill some species. The treatment also appears to dramatically reduce the abundance of algae and importantly does not appear to increases the total numbers of bacteria.

Rates and mechanism of corrosion under deoxygenated conditions – Laboratory experiments are underway to answer the following questions:

- How does deoxygenation affect bulk water chemistry, biofilm formation and biofilm/metal interfacial chemistry?

- Does microbiologically influenced corrosion occur under deoxygenated conditions and if so by what mechanisms?
- What is the impact of O_2 on corrosion that has developed under deoxygenated conditions? Does the mechanism shift? Is the rate accelerated?

Corrosion experiments with control and deoxygenated natural seawater are being conducted at the Naval Research Laboratory (NRL), Corrosion Facility, in Key West, FL and at the NRL, Stennis Space Center, MS. Individual tank are maintained with either oxygenated seawater (> 8.0 mg/l) or seawater that has passed through the rapid, in-line oxygen stripping system (0.8 mg/l oxygen) in a darkened anaerobic hood (Figure 3).

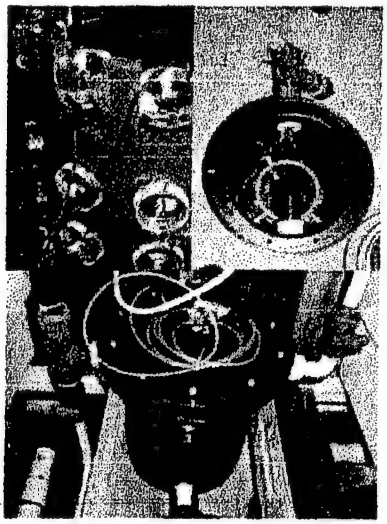

Figure 3. NRL corrosion experimental setup.

Samples are collected every two weeks over one year to assess changes in dissolved and particulate water chemistry (dissolved oxygen, dissolved organic carbon and nitrogen, particulate organic carbon and nitrogen, bulk pH, sulfide concentration) using standard techniques. Serial dilutions are used to determine most probable numbers of APB, SRB, general heterotrophic aerobes, and anaerobes (Bioindustrial technologies, Inc.). Carbon steel coupons are also exposed in each tank of oxygenated and deoxygenated natural seawater. Coupons have been orientated both horizontally and vertically to simulate tank bottoms and sidewalls, respectively. Triplicate samples from both containers are removed every two weeks, fixed in glutaraldehyde and examined to assess the extent of biofilm formation and corrosion morphology. Environmental scanning electron microscopy (ESEM) and energy dispersive spectroscopy (EDS) is being used to characterize the corrosion morphology, biofilm structure and corrosion product composition on the metal surface. Swabs made of the coupon surface and serial dilutions used to determine the microbial composition of the biofilm. Finally microelectrodes are used to make O_2 profiles through the biofilms. Polarization resistance and open-circuit potential will be used to monitor electrochemistry and corrosion over time.

CONCLUSION

Our fundamental goal is to provide the science necessary for the development of effective ballast water management strategies and policies. Through rigorous laboratory and dockside/mesocosm experiments, our work will provide the information required to evaluate the efficacy and feasibility of deoxygenation as a ballast water treatment to prevent aquatic invasions and will be the basis for a definitive shipboard study planned for the near future.

In summary, it appears that rapid and efficient reduction of oxygen levels in ballast water both cause substantial mortality of large proportion of transported organisms and minimizes ballast tank corrosion. As such, it may represent a rare example of a solution that simultaneously has benefits for marine conservation and industry.

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ACKNOWLEDGMENTS

We would like to thank K. Wasson, M. Matsuda, K. McPherson, and J. Lee for their help with various aspects of this work. The National Oceanic and Atmospheric Administration is funding our current investigations.

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and has developed designs for shipboard applications of Venturi Oxygen Stripping.

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